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SYSTEMATIC REVIEW

A systematic review of compositional data analysis studies examining associations between sleep, sedentary behaviour, and physical activity with health outcomes in adults[1]

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Abstract: This systematic review determined if the composition of time spent in movement behaviours (i.e., sleep, sedentary behaviour (SED), light physical activity, and moderate-to-vigorous physical activity (MVPA)) is associated with health in adults. Five electronic databases were searched in August 2019. Studies were eligible for inclusion if they were peer-reviewed, examined community-dwelling adults, and used compositional data analysis to examine the associations between the composition of time spent in movement behaviours and health outcomes. Eight studies (7 cross-sectional, 1 prospective cohort) of >12 000 unique participants were included. Findings indicated that the 24-h movement behaviour composition was associated with all-cause mortality (1 of 1 analyses), adiposity (4 of 4 analyses), and cardiometabolic biomarkers (8 of 15 analyses). Reallocating time into MVPA from other movement behaviours was associated with favourable changes to most health outcomes and taking time out of SED and reallocating it into other movement behaviours was associated with favourable changes to all-cause mortality. The quality of evidence was very low for all health outcomes. In conclusion, these findings support the notion that the composition of movement across the entire 24-h day matters, and that recommendations for sleep, SED, and physical activity should be combined into a single public health guideline. (PROSPERO registration no.: CRD42019121641.)

Novelty

- The 24-h movement behaviour composition is associated with a variety of health outcomes.
- Reallocating time into MVPA is favourably associated with health.
- Reallocating time out of SED is associated with favourable changes to mortality risk.

Key words: sleep, sedentary behaviour, physical activity, systematic review, public health, compositional data analysis, time-use epidemiology.

Résumé : Cette revue systématique détermine si la répartition du temps consacré aux comportements kinésiques (c.-à-d. le sommeil, le comportement sédentaire (« SED »), l'activité physique légère et l'activité physique modérée à vigoureuse (« MVPA »)) est associée à la santé des adultes. Cinq bases de données électroniques sont analysées en août 2019. Les études sont incluses si elles sont révisées par des pairs, étudient des adultes vivant dans la communauté et utilisent une analyse des données de composition pour examiner les associations entre la répartition du temps consacré aux comportements kinésiques et les résultats de santé. Huit études sont incluses (sept transversales, une cohorte prospective) comprenant >12 000 participants distincts. Les résultats indiquent que la répartition des comportements kinésiques sur 24 heures est associée à la mortalité toutes causes confondues (une analyse), à l'adiposité (quatre analyses sur quatre) et aux biomarqueurs cardiométaboliques (huit analyses sur quinze). La redistribution du temps dans les MVPA à partir d'autres comportements kinésiques est associée à des changements favorables à la plupart des résultats de santé et la réaffectation du comportement SED à d'autres comportements

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kinésiques est associée à des changements favorables à toutes causes confondues de mortalité. La qualité des données probantes est très faible pour tous les résultats de santé. En conclusion, ces résultats appuient la notion selon laquelle la répartition des comportements sur l'ensemble de la journée de 24 heures est importante et que les recommandations concernant le sommeil, le comportement SED et l'activité physique devraient être combinées en une seule directive de santé publique. (Numéro d'enregistrement PROSPERO : CRD42019119529.) [Traduit par la Rédaction]

Les nouveautés

- La répartition des comportements kinésiques sur 24 heures est associée à une variété de résultats pour la santé.
- La redistribution du temps à une activité physique modérée à vigoureuse est favorablement associée à la santé.
- La redistribution du temps hors du comportement sédentaire est associée à des changements favorables au risque de mortalité.

Mots-clés : sommeil, comportement sédentaire, activité physique, revue systématique, santé publique, analyse des données de composition, épidémiologie de l'emploi du temps.

Introduction

Sleep, sedentary behaviour, and physical activity, which will henceforth be referred to as movement behaviours, fall along an energy expenditure continuum (Chaput et al. 2014; Pedišić et al. 2017). Although research on the health effects of movement behaviours has historically focused on sleep (Alvarez and Ayas 2004) and moderate-to-vigorous physical activity (MVPA) (Pate et al. 1995; Warburton et al. 2010), since the beginning of the new millennium research has also considered whether time spent in sedentary behaviour (SED) and light physical activity (LPA) influences health (Owen et al. 2010; Tremblay et al. 2010). Furthermore, recent studies have examined how different combinations of movement behaviours relate to health outcomes. For instance, studies have considered whether time spent in SED is associated with health independent of time spent in MVPA (Owen et al. 2010; Tremblay et al. 2010) and whether replacing sedentary time with equal time from other movement behaviours benefits health (Del Pozo-Cruz et al. 2018).

A major flaw of most of the literature that has examined association between combinations of movement behaviours and health is that it has used statistical approaches that treat movement behaviours as independent of each other (Pedišić 2014). Movement behaviours are not independent of each other because together they form a composition with a fixed time of 24 h per day (Pedišić 2014; Chastin et al. 2015). Thus, if the amount of time spent in a movement behaviour is changed, that change must be offset by an equal but opposite change in some combination of the remaining movement behaviours (Pedišić 2014; Chastin et al. 2015). For instance, if an individual reduces their SED by 60 min per day, they must simultaneously increase the combined time they spend in sleep, LPA, and/or MVPA by a total of 60 min per day.

Compositional data analysis (CoDA) is a statistical technique that can be used to properly model the associations between movement behaviours and health outcomes. CoDA techniques are specifically designed to be used with compositional variables, such as the 24-h movement behaviour composition, which represents a fixed time of 24 h per day that is split between sleep, SED, LPA, and MVPA (Pedišić 2014; Chastin et al. 2015). In 2015, Chastin et al. published the first study that used CoDA statistical techniques to model the associations between movement behaviours and health outcomes. Findings from the Chastin et al. (2015) paper highlighted that the 24-h movement behaviour composition was collectively associated with a variety of cardiometabolic biomarkers and adiposity indicators, and that reallocating equivalent time from 1 movement behaviour to another was associated with changes in these health indicators. In the last 5 years, a number of studies have used CoDA approaches to examine the associations between movement behaviours and health outcomes. Although some of this evidence was included in 2 reviews published in 2018 (Del Pozo-Cruz et al. 2018; Grgic et al. 2018), these reviewers are now outdated as this is a rapidly developing field. Furthermore, in these 2 reviews the CoDA-based findings were embedded within broader literatures that were primarily based on non-CoDA studies. Therefore, a comprehensive and up-to-date review of CoDA studies in the movement behaviour field is warranted.

The purpose of this paper was to conduct a systematic review that considered whether the composition of time spent in sleep, SED, LPA, and MVPA is associated with health in adult populations. This review was conducted in large measure to provide evidence that would be used to help inform the development of the *Canadian 24-Hour Movement Guidelines for Adults aged 18–64 years and Adults aged 65 years or older* (Ross et al. 2020). We sought to review the best evidence and therefore limited our review to studies that used CoDA.

Materials and methods

Study context

This systematic review was conducted as part of a larger project that centred around the development of the *Canadian 24-Hour Movement Guidelines for Adults aged 18–64 years and Adults aged 65 years or older*. Details of that larger project and the guidelines are provided elsewhere in this issue of the journal (Ross et al. 2020). Within the context of the development of these new guidelines, this systematic review was conducted to (*i*) determine whether it is appropriate to combine recommendations for sleep, SED, and physical activity into a single guideline; and (*ii*) provide evidence to inform guideline statements related to the impact of replacing time spent in 1 movement behaviour with another, and to inform the health promotion messages that promote guideline adherence. Because this systematic review was being conducted as part of the *Canadian 24-Hour Movement Guidelines for Adults aged 18–64 years and Adults aged 65 years or older* project, several of the decisions around the inclusion/exclusion criteria, critical and important outcomes, and the approach used to grade quality of evidence were made so that the approaches used in this systematic review were consistent with those used in the 5 other reviews/overviews that were also conducted to help inform the 24-hour Movement Guidelines (Chaput et al. 2020*a*, 2020*b*; El-Kotob et al. 2020; McLaughlin et al. 2020; Saunders et al. 2020). A complete list of the decisions that were made for the full 24-hour Movement Guidelines project and not specific to this review can be found in the Supplementary materials.[2]

Protocol and registration

This systematic review was registered a priori with the International Prospective Register of Systematic Reviews (PROSPERO reg-

[2]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/apnm-2020-0160.

istration no. CRD42019121641). It was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement for reporting systematic reviews and meta-analyses (Moher et al. 2009).

Eligibility criteria

To facilitate the search process and identify key study concepts a priori, the Participants, Intervention/Exposure, Comparisons, Outcomes, Study design (PICOS) framework was used (Schardt et al. 2007).

Population

The population of interest was community-dwelling adults aged 18 years and older. This included apparently healthy adults, adults with obesity, adults with the metabolic syndrome, and adults who had fallen within the past year. This did not include studies that focused on a disease-specific population (e.g., only adults with cancer), pregnant women, residents of long-term care facilities, patients in acute care or a hospital setting, adults who were unable to move under their own power (e.g., paraplegia), and elite athletes. Studies with samples that included participants who met and did not meet the eligibility criteria were included if, based on our estimation, at least 80% of participants met the inclusion criteria or if the results pertaining to the population of interest were reported separately.

Intervention/exposure

The intervention/exposure of interest was the composition of time spent in sleep, SED, LPA, and MVPA. These movement behaviours were based on the measures and definitions used by the authors of the individual studies. For the most part, a cut-point of <1.5 metabolic equivalents (METs) during waking hours defined SED, a range of 1.5–2.99 METs defined LPA, and a cut-point of ≥3.0 METs defined MVPA. Based on these cut-points, quiet standing would be classified as LPA; however, quiet standing may have been incorrectly classified as SED in studies that measured movement behaviours using a waist-worn accelerometer (Healy et al. 2011). To be included, studies needed to have used a CoDA statistical approach and the composition needed to include at least 1 measure of sleep, 1 measure of SED, and 1 measure of physical activity or a measure of the full 24-h day broken down into time spent sleeping, in SED, and different intensities of physical activity. For experimental studies, the interventions may have targeted time spent in 1 or more movement behaviours as long as the time spent in all behaviours was reported in the paper. There were no restrictions placed on the methods used to measure the movement behaviours.

Comparison/control

The comparator was different compositions of time spent in sleep, SED, LPA, and MVPA. We also considered changes to the movement behaviour composition. This included changes observed in intervention studies and changes estimated from observational data (i.e., time reallocation estimates within a CoDA paradigm). For intervention studies, a control group was not required.

Outcomes

No limits were placed on the included health outcomes. Critical and important health outcomes were chosen based on the literature, expert input and consensus, and recognition of the importance of including a broad range of health outcomes for the reviews/overviews for sleep, SED, and physical activity that were conducted as part of the *Canadian 24-Hour Movement Guidelines for Adults aged 18–64 and Adults aged 65 years or older project* (Chaput et al. 2020*a*, 2020*b*; El-Kotob et al. 2020; McLaughlin et al. 2020; Saunders et al. 2020). Specifically, 15 critical outcomes were selected for this review because they were deemed critical outcomes for at least 1 of the sleep, SED, or physical activity reviews/overviews. Likewise, 4 outcomes were deemed important (but not critical) for at least 1 of the sleep, SED, or physical activity reviews/overviews. The 15 critical outcomes were mortality, quality of life, falls and related injuries, serious or nonserious adverse events, physical function and disability, brain health, cognitive function, mental health, cardiometabolic biomarkers, musculoskeletal pain, accidents and injuries, adiposity, cardiovascular disease, and type 2 diabetes. The 4 important outcomes were cancer, bone health, fatigue, and workplace productivity. Note that many of these critical and important outcomes themselves comprised several possible outcomes. For instance, the cardiometabolic biomarker outcome includes several measures of glucose and insulin control (e.g., fasting glucose, post-oral glucose tolerance test glucose, insulin resistance, etc.), several lipids and lipoproteins (e.g., triglycerides, low-density lipoprotein (LDL)-cholesterol, high-density lipoprotein (HDL)-cholesterol, etc.), systolic and diastolic blood pressure, etc. When there were several possible sub-outcomes within a critical or important outcome category, such as with the cardiometabolic biomarker and adiposity outcomes, the findings of all sub-outcomes were presented together under the broader outcome category and the quality of evidence for all of these sub-outcomes was assessed collectively. The collapsing of all sub-outcomes within an outcome category aided in streamlining the presentation of results and allowed us to give a similar emphasis and weighting to each of the critical outcomes when assessing the overall quality of evidence.

Study designs

With the exception of reviews, meta-analyses, and case studies, all study designs were eligible for inclusion, provided data were analyzed using CoDA, a branch of statistics that deals with data that represent parts or portions of a finite total (Aitchison 1982), and were parts of a whole that carry exclusively relative information (Barceló-Vidal and Martín-Fernández 2016). There were no restrictions placed on follow-up length in longitudinal studies or intervention length in intervention studies. There were no restrictions placed on sample sizes in any study design.

Information sources and search strategy

A research librarian with expertise in systematic review searching created the electronic search strategy. The Supplementary materials include an example of a complete search strategy.[2] The following databases were searched: MEDLINE, EMBASE, PsycINFO, CINAHL, and SPORTDiscus. Searches were conducted on August 16, 2019, and dated back to 2015, as that is when the first study on the association between the 24-h movement-behaviour composition and health outcomes was published (Chastin et al. 2015). We also searched our personal libraries and the reference lists of the studies that made it through level 2 screening. Studies were eligible for inclusion if they were published in English or French. Only published or in press peer-reviewed studies were included. Grey literature (e.g., book chapters, dissertations, conference abstracts) was excluded.

Study selection

Bibliographic records obtained in the electronic searches were imported into Reference Manager Software (Thomson Reuters, San Francisco, Calif., USA). Duplicate references were removed. In level 1 screening, titles and abstracts of all potentially relevant articles were screened by 2 independent reviewers using Covidence (Veritas Health Innovation, Melbourne, Australia). Articles meeting initial screening criteria by either reviewer proceeded to the full-text review at level 2 screening. The same 2 independent reviewers examined all of the full-text articles. Any discrepancies were resolved with a discussion and consensus between the 2 reviewers. A third reviewer was consulted if consensus could not be reached or if the original reviewers were uncertain about an article's eligibility.

Data extraction

Data were extracted from eligible articles into Microsoft Excel worksheet templates. This step was completed by 1 reviewer and verified by another. Reviewers were not blinded to the authors or journals when extracting data. For each study, we extracted data on the study results and important study features, including the study design, population of interest, sample size, age range of participants, methods used to measure the movement behaviours and health outcomes, and covariates that were controlled for. We also extracted information on whether the studies reported different findings according to age, sex, race/ethnicity, socioeconomic status, weight status, and/or chronic disease status. When the results of multiple regression models were reported, results from the most fully adjusted models were extracted unless the reviewer deemed that the most fully adjusted model controlled for variables that were on the causal pathway between the exposure and outcome, in which case the results of a more appropriate regression model were extracted. This only happened for 1 article (McGregor et al. 2019*a*). For that article we also contacted the first author to provide us with some of the pertinent information for our review that was missing from the article.

Risk of bias and study quality assessment

Risk of bias and quality assessment were completed using accepted tools and processes under the guidance of 2 systematic review methodology experts. All assessments were verified, and modified if necessary, by the authorship team and expert panel responsible for drafting the *Canadian 24-Hour Movement Guidelines for Adults and Older Adults*. Risk of bias assessment was completed using the methods described in the Cochrane Handbook (Higgins and Green 2011). Risk of bias assessments were completed by 2 reviewers and were performed separately for each study for each of the different outcomes. The detailed risk of bias assessments for each study within each of the outcomes are in the Supplementary materials[2] (Table S1 for mortality, Table S2 for adiposity, Table S3 for cardiometabolic biomarkers, Table S4 for mental health). The quality of evidence for each health outcome was determined in a systematic manner using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework (Guyatt et al. 2011). GRADE categorizes the quality of evidence into 4 groups ("high", "moderate", "low", and "very low"). The rating starts at "high" for randomized studies and at "low" for all other studies. The quality of evidence can be downgraded if there are serious limitations across studies such as serious risk of bias, inconsistency of effects, indirectness, or imprecision. The quality of evidence can be upgraded if there is no cause for downgrading and a large effect size and/or a dose–response relationship (Guyatt et al. 2011).

Rating system used for interpretation of results and synthesis of results

We faced 2 challenges when determining what approach to use to synthesize and summarize the results. The first challenge reflected that for CoDA-based papers examining the 4-part movement behaviour composition there are at least 17 parameters that are commonly interpreted in relation to the outcome variable. These parameters include (*i*) a result that reflects whether the 24-h movement behaviour composition as a whole is related to the health outcome; (*ii*) 4 results that reflect whether the relative contributions of MVPA, LPA, SED, and sleep are associated with the health outcome; and (*iii*) 12 results that reflect whether different time reallocations are associated with changes in the health outcomes (e.g., reallocating time from MVPA to LPA, reallocating time from LPA to MVPA, reallocating time from MVPA to SED, etc.). The second challenge we faced when summarizing the results reflected that the review included several health outcomes and sub-outcomes. For some of these health outcomes and sub-outcomes (e.g., HDL-cholesterol, insulin sensitivity) a positive association would be considered favourable for health, while for some health outcomes and indicators (e.g., LDL-cholesterol, insulin resistance) a negative association would be considered favourable for health.

To simplify and standardize the presentation of findings, we presented the results for each of the individual parameters of interest as either an upward pointing arrow (↑), a sideways pointing arrow (↔), or downward pointing arrow (↓). For results based on the 24-h movement behaviour composition, which is based on a model fit statistic that does not consider directionality, ↑ denoted the presence of a result that was statistically significant while ↔ denoted the presence of a result that was not statistically significant. For the results based on the relative contributions of each movement intensity and the results for the time reallocations, ↑ denoted the presence of a result that was statistically significant and favourable for health (e.g., relative time spent in MVPA was associated with a significant decrease in mortality risk), ↔ denoted the presence of a result that was not statistically significant (e.g., relative time spent in sleep was not significantly associated with mortality risk), and ↓ denoted the presence of a result that was statistically significant and unfavourable for health (e.g., relative time spent in SED was associated with a significant increase in mortality risk).

For each health outcome a ↑/↔/↓ rating system was also used to summarize the overall pattern of results for the 24-h movement behaviour composition, relative time spent in each of the 4 movement behaviours, and each of the 12 time reallocations. The determination of the overall ratings for each health outcome started by applying scores of 1, 0, and –1 to each of the individual ↑, ↔, and ↓ ratings. Scores were summed and then were divided by the total number or ratings. For the results based on the 24-h movement behaviour composition, the final calculated values for each health outcome could range between 0 and 1. When the final value was 0.66 or higher the overall pattern was rated ↑ and when the final value was 0.65 or lower the overall pattern was rated ↔. For the results based on the relative contributions of each movement behaviour and the time reallocations, the final calculated value for each health outcome could range from –1 to 1. When the final value was 0.33 or higher the overall pattern was rated ↑, when the final value was between –0.32 and 0.32 the overall pattern was rated ↔, and when the final value was –0.33 or lower the overall pattern was rated ↓.

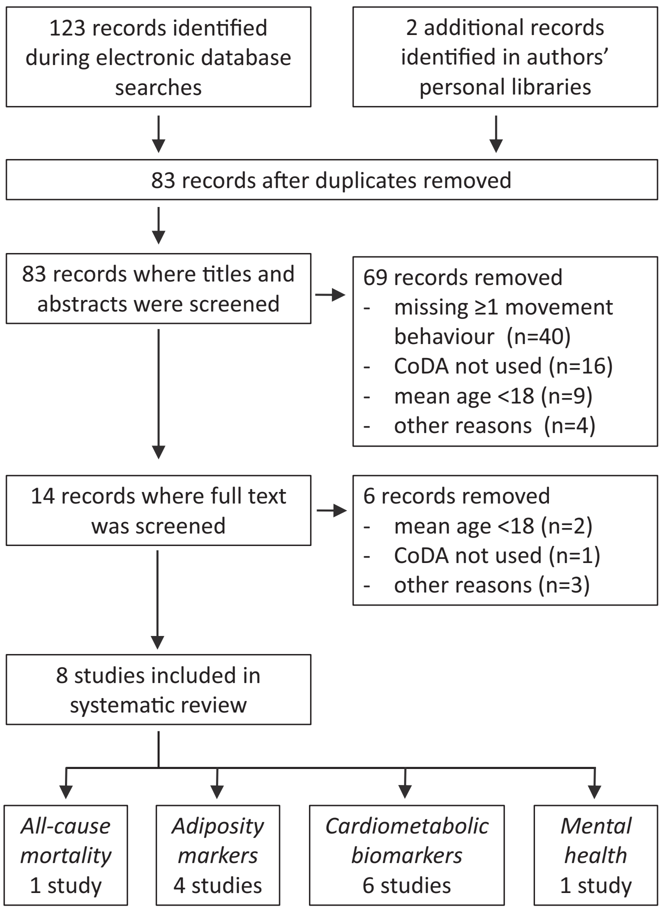
Meta-analyses were considered for the time reallocation findings if a sufficient number of studies used comparable time reallocation estimation approaches on the same outcomes. As there were too few studies and considerable heterogeneity in time reallocation approaches a meta-analysis was ultimately not performed. Therefore, narrative syntheses structured around the health outcomes were presented using the aforementioned ↑/↔/↓ rating systems.

Results

Description of studies

As illustrated in Fig. 1, 123 studies were identified through the database searches (MEDLINE, n = 27; EMBASE, n = 50; PsycINFO, n = 7; CINAHL, n = 34; SPORTDiscus, n = 5) and an additional 2 newly published studies were identified from the authors' personal libraries. After duplicates were removed, there were 83 unique studies. After titles and abstracts were screened in level 1, 14 full-text articles were obtained for level 2 screening. Eight studies passed level 2 screening and were included in this systematic review (Chastin et al. 2015; Biddle et al. 2018; Dumuid et al. 2018; Gupta et al. 2018, 2019; McGregor et al. 2018, 2019*a*; Powell et al. 2020). The top 3 reasons for excluding studies were missing 1 or more movement intensity (n = 40), CoDA statistical techniques were not used (n = 17), and the mean age of participants was less

Fig. 1. Flow diagram of article searches and screening. CoDA, compositional data analysis.



than 18 years (n = 11). Many studies were excluded for more than 1 reason.

Characteristics of the 8 studies included in this review are summarized in Table 1. The samples in these studies ranged from a small convenience sample of 122 participants (Dumuid et al. 2018) to a large and nationally representative sample of 7776 participants (McGregor et al. 2018). Data across studies involved >12 000 unique participants from 5 countries (Australia, Canada, Denmark, Ireland, United States); there was considerable overlap of participants in the Chastin et al. (2015) and McGregor et al. (2019*a*) studies as well as the 2 studies by Gupta et al. (Gupta et al. 2018, 2019). Seven of the studies used cross-sectional designs (Chastin et al. 2015; Biddle et al. 2018; Dumuid et al. 2018; Gupta et al. 2018, 2019; McGregor et al. 2018; Powell et al. 2020) and the remaining study was a longitudinal cohort study (McGregor et al. 2019*a*). Sleep was primarily assessed using self-reports, while SED, LPA, and MVPA were assessed using either an activPAL device (Biddle et al. 2018; Powell et al. 2020) or ActiGraph device (Chastin et al. 2015; Dumuid et al. 2018; Gupta et al. 2018, 2019; McGregor et al. 2018, 2019*a*).

The 8 studies examined 4 critical outcomes, no important outcomes, and no outcomes that were not defined as critical or important a priori. Note that most of the studies examining adiposity and cardiometabolic biomarkers examined multiple sub-outcomes (e.g., adiposity studies often measured both the body mass index and waist circumference) and in 1 study the analyses were stratified into adults aged 18–64 years versus adults aged 65–79 years. In total across all of the 8 studies included in this review, 1 association between the movement behaviour composition and mortality was presented, 9 associations between the movement behaviour composition and adiposity were presented, 40 associations between the movement behaviour composition and cardiometabolic biomarkers were presented, and 2 associations between the movement behaviour composition and mental health were presented. In some of the studies included in the review, results were not presented for all of the associations of interest. This included 3 studies that did not report whether the 24-h movement behaviour composition was associated with the health outcomes (Biddle et al. 2018; McGregor et al. 2018; Powell et al. 2020), 1 study that did not report findings on time reallocations for any health outcomes (McGregor et al. 2018), and 2 studies that reported findings on time reallocations for some but not of the health outcomes that were examined (Dumuid et al. 2018; Gupta et al. 2018). Of the 5 studies that presented findings for time reallocations, 1 used the model described by Chastin et al. (2015), 2 used the model described by Dumuid et al. (2018), 1 used the model described by McGregor et al. (2019*a*), and 1 did not provide enough detail to determine what model was used. Furthermore, the 2019 study by Gupta et al. examined the same outcomes (blood pressure) in a smaller subsample of that used in the 2018 study by Gupta et al. Therefore, when summarizing the results for the cardiometabolic biomarkers outcome only the results from the 2018 study by Gupta et al. were used.

Data synthesis

Supplementary Table S5[2] contains the results on each of the individual associations between the full 24-h movement behaviour composition and health outcomes. Table S5 also contains the results for each of the published associations between the relative contributions of sleep, SED, LPA, and MVPA and health outcomes. Supplementary material Table S6[2] contains the results for each of the published associations between the time reallocations and health outcomes, which reflects the estimated changes in the health outcomes that would occur if equivalent time was reallocated from 1 intensity of movement into another (e.g., decreasing SED by 30 min per day while simultaneously increasing MVPA by 30 min per day). A summary of the findings presented in Supplementary Tables S5 and S6[2] are provided in Table 2 and in the text below.

Mortality

One prospective cohort study of a nationally representative sample of 1592 American adults examined the association between the movement behaviour composition and all-cause mortality (McGregor et al. 2019*a*). That study reported that the 24-h movement behaviour composition was collectively associated with mortality risk (↑), MVPA and LPA relative to the other movement behaviours were favourably associated with mortality risk (↑), SED relative to the other movement behaviours was unfavourably associated with mortality risk (↓), and sleep relative to the other movement behaviours was not associated with mortality risk (↔). The time reallocation estimates suggested that reallocating equivalent time into MVPA from any of the remaining movement behaviours was associated with a reduced mortality risk (↑), reallocating equivalent time into SED from any of the other movement behaviours was associated with an increased mortality risk (↓), and reallocating equivalent time from sleep into LPA was associated with an increased mortality risk (↓). The quality of evidence for mortality was downgraded from low to very low because of concerns around attrition bias, residual confounding, and serious imprecision (Table 3 and supplementary Table S1[2]).

Adiposity

Four cross-sectional studies of 10 201 participants from 4 countries examined the association between the movement behaviour composition and adiposity measures such as body mass index, waist circumference, waist-to-hip ratio, and body fat (Chastin et al. 2015; Dumuid et al. 2018; McGregor et al. 2018; Powell et al. 2020). The

Table 1. Description of studies included in the systematic review.

		Sample characteristics			Movement behaviour measures				
Reference	Study design	Description	Sample size	Age range (y)	MVPA	LPA	SED	Sleep	Health outcomes
Biddle et al. (2018)	Cross-sectional	Patients at high risk for diabetes from general practices in UK	435	33–78	4–7 d by activPAL[a]	4–7 d by activPAL[a]	4–7 d by activPAL	4–7 d by activPAL	GLU, 2-h GLU, INS, 2-h INS, HOMA-IS, Matsuda-ISI
Chastin et al. (2015)	Cross-sectional	Representative sample of US	1937 (894)[b]	21–64	5–7 d by ACCEL	5–7 by ACCEL	5–7 d by ACCEL	Typical night by questionnaire	WC, BMI, SBP, DBP HDL-C, CRP; LDL-C, TRI, GLU, INS, HOMA
Dumuid et al. (2018)	Cross-Sectional	Older adults from Australia	122	60–70	4–7 d by ACCEL	4–7 d by ACCEL	4–7 d by ACCEL	4–7 d by ACCEL and sleep diary	BMI, WHR, TC, SBP, DBP GLU
Gupta et al. (2018)	Cross-sectional	Danish workers	827	NR	1–4 d by ACCEL	1–4 d by ACCEL	1–4 d by ACCEL	4–7 d by ACCEL and sleep diary	SBP, DBP
Gupta et al. (2019)	Cross-sectional	Danish blue-collar workers	669	NR	1–4 d by ACCEL	1–4 d by ACCEL	1–4 d by ACCEL	1–4 d by ACCEL and sleep diary	SBP, DBP
McGregor et al. (2018)	Cross-sectional	Representative sample of Canadians	6322 (2833);[c] 1454 (697)[c]	18–64; 65–79	4–7 d by ACCEL	4–7 d by ACCEL	4–7 d by ACCEL	Typical night by questionnaire	WC, BMI, SBP, DBP, RHR, HDL-C, LDL-C, CRP, INS, GLU, mental health
McGregor et al. (2019*a*)	Prospective cohort	Representative sample of US	1592	50–79	1–7 d by ACCEL	1–7 d by ACCEL	1–7 d by ACCEL	Typical night by questionnaire	All-cause mortality
Powell et al. (2020)	Cross-sectional	Random sample from general practices in Ireland	366	55–74	4–7 d by activPAL	4–7 d by activPAL	4–7 d activPAL	4–7 d by activPAL	GLU, HbA1c, TC, LDL-C, VLDL-C, TRI, BMI, % body fat, fat mass

Note: ACCEL, accelerometer; BMI, body mass index; CRP, C-reactive protein; DBP, diastolic blood pressure; GLU, glucose; HbA1c, Glycated haemoglobin; HDL-C, high-density lipoprotein cholesterol; HOMA, homeostasis model assessment of insulin resistance; HOMA, homeostasis model assessment; HOMA-IS, homeostasis model assessment of insulin sensitivity; INS, insulin; LPA, light physical activity; LDL-C, low-density lipoprotein cholesterol; Matsuda-ISI, Matsuda Insulin Sensitivity Index; MVPA, moderate-to-vigorous physical activity; NR, not reported; RHR, resting heart rate; SBP, systolic blood pressure; SED, sedentary time; TC, total cholesterol; TRI, triglycerides; UK, United Kingdom; US, United States; VLDL-C, very-low-density lipoprotein cholesterol; WC, waist circumference; WHR, waist to hip ratio.

[a]For this study stepping was equivalent to MVPA and standing was equivalent to LPA.

[b]Subsample used for analysis of CRP, HDL-C, LDL-C, TRI, GLU, INS, and HOMA outcomes.

[c]Subsample used for analysis of CRP, HDL-C, LDL-C, TRI, GLU, and INS outcomes.

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Table 2. Summary of results for each health outcome.

24-h movement behaviour composition and its components	Time reallocations between movement behaviours
All-cause mortality	
Composition: ↑ (1), ↔ (0)	MVPA to LPA: ↑ (0), ↔ (0), ↓ (1)
MVPA: ↑ (1), ↔ (0), ↓ (0)	LPA to MVPA: ↑ (1), ↔ (0), ↓ (0)
LPA: ↑ (1), ↔ (0), ↓ (0)	MVPA to SED: ↑ (0), ↔ (0), ↓ (1)
SED: ↑ (0), ↔ (0), ↓ (1)	SED to MVPA: ↑ (1), ↔ (0), ↓ (0)
Sleep: ↑ (0), ↔ (1), ↓ (0)	MVPA to sleep: ↑ (0), ↔ (0), ↓ (1)
	Sleep to MVPA: ↑ (1), ↔ (0), ↓ (0)
	LPA to SED: ↑ (0), ↔ (0), ↓ (1)
	SED to LPA: ↑ (1), ↔ (0), ↓ (0)
	LPA to sleep: ↑ (0), ↔ (0), ↓ (1)
	Sleep to LPA: ↑ (0), ↔ (0), ↓ (1)
	SED to sleep: ↑ (1), ↔ (0), ↓ (0)
	Sleep to SED: ↑ (0), ↔ (0), ↓ (1)
Adiposity	
Composition: ↑ (4), ↔ (0)	MVPA to LPA: ↑ (0), ↔ (3), ↓ (4)
MVPA: ↑ (6), ↔ (3), ↓ (0)	LPA to MVPA: ↑ (4), ↔ (3), ↓ (0)
LPA: ↑ (3), ↔ (4), ↓ (2)	MVPA to SED: ↑ (0), ↔ (3), ↓ (4)
SED: ↑ (0), ↔ (6), ↓ (3)	SED to MVPA: ↑ (4), ↔ (0), ↓ (3)
Sleep: ↑ (1), ↔ (8), ↓ (0)	MVPA to sleep: ↑ (0), ↔ (3), ↓ (4)
	Sleep to MVPA: ↑ (3), ↔ (4), ↓ (0)
	LPA to SED: ↑ (0), ↔ (3), ↓ (4)
	SED to LPA: ↑ (3), ↔ (4), ↓ (0)
	LPA to sleep: ↑ (2), ↔ (2), ↓ (3)
	Sleep to LPA: ↑ (3), ↔ (2), ↓ (2)
	SED to sleep: ↑ (3), ↔ (4), ↓ (0)
	Sleep to SED: ↑ (0), ↔ (4), ↓ (3)
Cardiometabolic biomarkers	
Composition: ↑ (9), ↔ (7)	MVPA to LPA: ↑ (7), ↔ (10), ↓ (6)
MVPA: ↑ (16), ↔ (26), ↓ (0)	LPA to MVPA: ↑ (5), ↔ (15), ↓ (3)
LPA: ↑ (4), ↔ (38), ↓ (0)	MVPA to SED: ↑ (2), ↔ (11), ↓ (9)
SED: ↑ (0), ↔ (41), ↓ (1)	SED to MVPA: ↑ (18), ↔ (14), ↓ (1)
Sleep: ↑ (6), ↔ (28), ↓ (8)	MVPA to sleep: ↑ (4), ↔ (9), ↓ (10)
	Sleep to MVPA: ↑ (9), ↔ (12), ↓ (2)
	LPA to SED: ↑ (2), ↔ (16), ↓ (5)
	SED to LPA: ↑ (5), ↔ (18), ↓ (0)
	LPA to sleep: ↑ (5), ↔ (14), ↓ (4)
	Sleep to LPA: ↑ (5), ↔ (13), ↓ (5)
	SED to sleep: ↑ (3), ↔ (16), ↓ (3)
	Sleep to SED: ↑ (3), ↔ (15), ↓ (5)
Mental health	
Composition: Not reported	Not reported
MVPA: ↑ (1), ↔ (1), ↓ (0)	
LPA: ↑ (0), ↔ (2), ↓ (0)	
SED: ↑ (0), ↔ (2), ↓ (0)	
Sleep: ↑ (0), ↔ (2), ↓ (0)	

Note: ↑, The overall pattern of all associations examined in the literature was favourable for health outcomes. ↔, The overall pattern of all associations examined in the literature was null, neither favourable or unfavourable, or largely inconsistent. ↓, The overall pattern of all associations examined in the literature was unfavourable for health outcomes. LPA, light physical activity; MVPA, moderate-to-vigorous physical activity; SED, sedentary time.

association between the 24-h movement behaviour composition and adiposity was rated as ↑ since 4/4 associations presented in the literature were significant. The associations between MVPA relative to the other movement behaviours and adiposity were also rated as ↑ while the associations for SED were rated as ↓ and the associations for sleep and LPA were rated as ↔. The time reallocation estimates suggested that reallocating equivalent time into MVPA from any of the remaining movement behaviours was associated with favourable changes in adiposity (↑), reallocating equivalent time into SED from MVPA or LPA was associated with unfavourable changes in adiposity (↓), and that time reallocations between LPA and sleep were not associated with adiposity (↔). The quality of evidence for adiposity was downgraded from low to very low because of serious risk of bias and imprecision (Table 3 and supplementary Table S2[2]).

Cardiometabolic biomarkers

Seven cross-sectional studies of 6174 participants from 5 countries examined the association between the movement behaviour composition and cardiometabolic biomarkers, including measures of glucose and insulin control, lipids and lipoproteins, blood pressure, C-reactive protein, and resting heart rate (Chastin et al. 2015; Biddle et al. 2018; Dumuid et al. 2018; Gupta et al. 2018, 2019; McGregor et al. 2018; Powell et al. 2020). Collectively, the association between the 24-h movement behaviour composition and cardiometabolic biomarkers was rated as ↔; while 8 of the 15 associations reported in the literature were significant ($p < 0.05$) the remaining 7 were nonsignificant ($p > 0.05$). The associations between the sleep, SED, and LPA (relative to the other movement behaviours) and cardiometabolic biomarkers were also rated as ↔. Conversely, the association between MVPA (relative to the other movement behaviours) and cardiometabolic biomarkers was rated as ↑. Reallocating time from sleep or SED into MVPA was rated as ↑; reallocating time from MVPA into sleep or SED was rated the opposite (↓). All other time reallocations were rated as ↔. The quality of evidence was downgraded from low to very low because of serious risk of bias and inconsistency (Table 3 and supplementary Table S3[2]).

Mental health

One cross-sectional study of a representative sample of 7776 Canadian adults examined the association between the movement behaviour composition and self-reported mental health (McGregor et al. 2018). In that study, MVPA relative to the other movement behaviours was favourably associated with mental health in 65–79-year olds (↑) but not in 18–64-year olds (↔). The relative contributions of sleep, SED, and LPA were not associated with mental health in 18–64- or 65–79-year olds (↔). Associations for the overall 24-h movement behaviour composition and time reallocations were not presented. The quality of evidence for mental health was downgraded from low to very low because of serious concerns of bias and inconsistency (Table 3 and supplmentary Table S4[2]).

Variation of effect by sociodemographic and health characteristics

No studies examined whether the associations between the movement behaviour composition and health outcomes differed by sex, race/ethnicity, socioeconomic status, weight status, and/or chronic disease status. One study provided information on potential effect modification related to age (McGregor et al. 2018). That study conducted analyses in 2 separate age strata (18–64-year olds and 65–79-year olds). Although there were some subtle nuances, the overall pattern of results did not present a picture of the 24-h movement behaviour composition being a weaker or stronger predictor of health outcomes in 1 age group versus the other.

High-level summary of findings

A high-level summary of findings for the 24-h movement behaviour composition and each of its components is presented in Table 4. Collectively, the findings suggest a ↑ rating for the 24-h movement behaviour composition (overall pattern of ↑ for 2/3 outcomes and ↔ for 1/3 outcomes), a ↑ rating for MVPA relative to the other movement behaviours (overall pattern of ↑ for 4/4 outcomes), a ↔ rating for LPA relative to the other movement behaviours (overall pattern of ↔ for 3/4 outcomes and ↑ for 1/4 outcomes), a ↔ rating for SED relative to the other movement behaviours (overall pattern of ↔ for 2/4 outcomes and ↓ for 2/4 outcomes), and a ↔ rating for sleep relative to the other movement behaviours (overall pattern of ↔ for 4/4 outcomes). While the overall ratings for the individual movement behaviour com-

Table 3. Quality assessment of studies examining the relationship between the movement behaviour composition and its components with health outcomes.

Health outcome	No. of studies	No. of unique participants[a]	No. of health outcome associations[b]	Quality assessment: Serious risk of bias	Serious risk of inconsistency	Serious risk of indirectness	Serious risk of imprecision	Quality
All-cause mortality	1	1468	1	No	NA	No	Yes	Very low
Adiposity	4	10 201	9	Yes	Yes	No	No	Very low
Cardiometabolic biomarkers	7	6174	40	Yes	Yes	No	No	Very low
Mental health	1	7776	2	Yes	Yes	No	No	Very low

[a]For the No. of unique participants calculation for cardiometabolic biomarkers, participants from Gupta et al. (2018) were included while participants from Gupta et al. (2019), which were all included in Gupta et al. (2018), were excluded. The 2019 study was an analysis of the same health outcomes (systolic and diastolic blood pressure) in a subsample of participants form the 2018 study.

[b]For the No. of health outcome associations calculation, if a study examined associations between the movement behaviour composition and more than 1 adiposity, cardiometabolic biomarker, or mental health outcome, it contributed to multiple counts. Because Gupta et al. (2018) and Gupta et al. (2019) examined associations between the movement behaviour composition and blood pressure outcomes in the same sample, only the associations from Gupta et al. (2018) were included in the count for cardiometabolic biomarkers. Because McGregor et al. (2018) conducted analyses separately in 18–64-year olds and 65–79-year olds, it counted 2 towards the total for each outcome examined.

Table 4. Summary of results for the movement behaviour composition and each of its components.

Health outcome	Movement behaviour composition	MVPA relative to other movement intensities	LPA relative to other movement intensities	SED relative to other movement intensities	Sleep relative to other movement intensities
All-cause mortality	↑	↑	↑	↓	↔
Adiposity	↑	↑	↔	↓	↔
Cardiometabolic biomarkers	↔	↑	↔	↔	↔
Mental health	Not reported	↑	↔	↔	↔

Note: ↑, The overall pattern of all associations examined in the literature was favourable for health outcomes. ↔, The overall pattern of all associations examined in the literature was null or neither favourable or unfavourable for health outcomes. ↓, The overall pattern of all associations examined in the literature was unfavourable for health outcomes. LPA, light physical activity; MVPA, moderate-to-vigorous physical activity; SED, sedentary time.

ponents were mostly neutral, as discussed below, the ratings for the time reallocations were more illuminating.

A high-level summary of findings for the time reallocations is presented in Table 5. The overall pattern of findings when considering all associations for all health outcomes suggests that it is favourable (↑) to reallocate time into MVPA and unfavourable (↓) to take time out of MVPA, irrespective of what other movement behaviour MVPA is reallocated out of or into. Evidence also suggests that, at least for the mortality outcome, that reallocating time from SED into sleep would be favourable (↑) while shifting time from physical activity into sleep would be unfavourable (↓).

Table 5. Summary of results for the time reallocations.

	Time removed from: MVPA	LPA	SED	Sleep
Time added to:				
MVPA	—	↑↑↔	↑↑↑	↑↑↑
LPA	↓↓↔	—	↑↑↑	↑↔↔
SED	↓↓↓	↓↓↔	—	↓↔↔
Sleep	↓↓↓	↓↔↔	↑↔↔	—

Note: The first arrow in each cell represents the overall pattern of results for all-cause mortality. The second arrow represents the overall pattern for adiposity. The third arrow represents the overall pattern for cardiometabolic biomarkers. ↑, The overall pattern of all associations examined in the literature was favourable for health outcomes. ↔, The overall pattern of all associations examined in the literature was null, neither favourable or unfavourable or the findings were largely inconsistent. ↓, The overall pattern of all associations examined in the literature was unfavourable for health outcomes. LPA, light physical activity; MVPA, moderate-to-vigorous physical activity; SED, sedentary time.

Discussion and conclusions

The decision to move away from separate public health guidelines for individual movement behaviours to a single 24-h movement guideline that encompasses all movement behaviours was made, in part, under the assumption that movement across the whole day matter (Ross et al. 2020). Thus, the findings from this review that the 24-h movement behaviour composition is associated with health and that reallocating time across different movement behaviours is associated with health, provides evidence that supports the decision to package recommendations for sleep, SED, and physical activity into the *Canadian 24-hour Movement Guidelines for Adults aged 18–64 years and Adults aged 65 years or older*. The growing body of evidence linking health to the movement behaviour composition also provides justification for the importance of measuring movement across the full 24-h day, using CoDA statistical techniques in movement behaviour research, and conducting time-use epidemiology research.

Of all movement behaviours, the most consistent results were for the relative contribution of MVPA. In this review, MVPA received an overall ↑ rating for all 4 health outcomes, indicating that the health outcomes improved as the relative contribution of MVPA to the 24-h movement behaviour composition increased. Conversely, the relative contributions of sleep, SED, and LPA to the movement behaviour composition mostly received ↔ ratings, indicating that the relative contributions of these movement behaviours were mostly not significantly associated with the health outcomes in a favourable or unfavourable direction.

The use of time reallocation modelling within a CoDA analysis framework has allowed researchers to use observational data to estimate how health outcomes would change if time spent in 1 movement behavour was displaced by equivalent time spent in the others. Seven of the 8 studies examined in this review included the results from time reallocation models (Chastin et al. 2015; Biddle et al. 2018; Dumuid et al. 2018; Gupta et al. 2018, 2019; McGregor et al. 2019*a*; Powell et al. 2020). Collectively, the results of these models suggest that time reallocations would always favour reallocating time into MVPA and reallocating time out of SED. If sleep duration is insufficient, health outcomes would most likely improve if time was reallocated into sleep from SED but not if it was reallocated from physical activity. If sleep is sufficient and physical activity is insufficient, health outcomes would most likely improve if sleep is preserved and physical activity levels are increased by reducing SED during waking hours. These findings have important implications for public health messages around how to improve the 24-h movement behaviour composition.

CoDA statistical techniques have only been used over the last 5 years to examine how movement behaviours across the full 24-h day are associated with health (Chastin et al. 2015) and therefore the volume of research is still quite small and future research is warranted. In particular, more longitudinal research is needed, and the effects of experimentally induced changes to the movement behaviour composition on health should also be studied. Existing research has primarily focused on adiposity and cardiometabolic biomarkers and future studies should consider other health outcomes. Only 1 of the existing studies considered whether the associations between the 24-h movement behaviour composition and health vary by age (McGregor et al. 2018), and future studies should consider whether these associations vary across a range of sociodemographic (e.g., age, sex, race/ethnicity, socioeconomic status) and health factors (e.g., obesity, chronic disease status). Based on the GRADE framework, the quality of evidence was rated as very low for all health outcomes. Aside from using longitudinal and intervention studies, to improve upon the quality of evidence, future studies should reduce bias by using valid approaches for measuring all movement behaviours and not just MVPA. Accelerometers do not distinguish between sitting and standing still, which leads to measurement bias for SED and LPA (Healy et al. 2011). This could bias results in favour of the relative contribution of MVPA versus other movement behaviours. Finally, future observational studies need to do a more thorough job of measuring and controlling for potential confounding variables as the list of confounding variables considered in most of the existing studies was incomplete (e.g., diet was often not controlled for).

Our systematic review was limited to papers published in the peer reviewed literature. This creates a potential for publication bias, since studies with null findings are less likely to be published (Sterne et al. 2001). This review was also limited to papers published in English or French; however, a recent study reported that excluding non-English publications from evidence syntheses did not change the conclusions (Nussbaumer-Streit et al. 2020). We limited our review to papers that included at least 1 measure of sleep, SED, and physical activity. A growing body of movement behaviour CoDA studies that excluded 1 movement behaviour – in most instances sleep – was not included in this review (Rodriguez-Gomez et al. 2018; Amagasa et al. 2019; McGregor et al. 2019*a*, 2019*b*; von Rosen et al. 2020). Furthermore, while the ↑/↔/↓ rating system used in this review allowed us to present a large volume of complex findings in a simple and easily understandable way, this approach was based entirely on statistical significance, while information on the effect sizes and their variability was not taken into account. Finally, some of the inconsistent findings for these cardiometabolic biomarker and adiposity outcomes may have been attributed to the fact that we grouped together the findings from all cardiometabolic biomarkers and all adiposity markers together into single outcomes.

In conclusion, the use of CoDA statistical techniques in movement behaviour research has provided novel and exciting findings on how movement across the entire 24-h day is associated with health. Existing evidence suggests that the 24-h movement behaviour composition is associated with health and provides support for combining recommendations for sleep, SED, and physical activity into a single public health guideline such as the *Canadian 24-Hour Movement Guidelines for Adults aged 18–64 years and Adults aged 65 years or older*. Existing evidence also suggests that reallocating time into MVPA and out of SED, while preserving sufficient sleep, would benefit health. However, the volume and quality of evidence is very low, and future research should build upon the gaps and limitations identified in this review.

Conflict of interest statement

A.E.C. reports grants from Public Health Agency of Canada/Canadian Society for Exercise Physiology and a graduate award from Queen's University during the conduct of the study. L.M.G. reports grants from Public Health Agency of Canada during the conduct of the study. M.E.K. reports personal fees and other from Canadian Society for Exercise Physiology during the conduct of the study. V.J.P. reports personal fees from Canadian Society for Exercise Physiology during the conduct of the study. V.J.P. also reports that she is a Canadian Agency for Drugs and Technology in Health (CADTH) employee, that the current work was unrelated to her employment, and that CADTH had no role in the funding, design, or oversight of the work reported. T.J.S. reports grants from Public Health Agency of Canada, Queen's University, and the Canadian Society for Exercise Physiology during the conduct of the study. T.J.S. also reports personal fees from the Public Health Agency of Canada, the Public Schools Branch of PEI, and travel funding from Ergotron outside the submitted work. A.R.-W. reports personal fees from ProQuest LLC outside the submitted work. The remaining authors declare that they have no conflicts of interest.

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